BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 11031

SUBJECT: Astronaut Wire Communication Link During Lunar Explorations - Case 320

DATE: November 13, 1969

FROM: W. J. Benden

ABSTRACT

In forthcoming lunar explorations, the astronaut will probably descend several hundred meters into craters and rills, as well as travel on flat surfaces well beyond line-of-sight of the Lunar Module. The present r-f communication system needs to be augmented in some manner to provide continuous communications during these explorations.

This memorandum discusses the possibilities of using hard-wire for the transmission of voice and biomedical data. The system, called the Astronaut's Wire-Link (AWL), is to be used in parallel with the present VHF communication system. Of course, its transmission properties are independent of lunar terrain variations.

The author draws upon his past experience in the wire guidance of torpedoes and rockets. An AWL is selected which is basically an "off-the-shelf" item and its electrical and physical characteristics are calculated. The insulated wire, selected for a 40,000 ft. AWL, will weigh close to ten pounds.

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MEMORANDUM FOR FILE

I. INTRODUCTION

The author, having some past experience in the wire guidance of torpedoes and anti-tank missiles, was asked to take a look at the possibilities of sending the astronaut's voice and biomed signals* over 12 kilometers of hard-wire during lunar exploration. Clearly, an Astronaut Wire-Link (AWL) would not be affected by the hills and rills of the lunar surface (no line-of-sight problems).

As in most all communications systems, particular emphasis must be placed on minimum weight, volume, signal losses and development time. The author feels that these goals are approached closely with the techniques discussed in this memorandum. Some of these techniques, however, are believed to be original and may be proven impractical. The basic concept, however, of sending electrical signals over a wire-link, while it is being unwound from a coiled state, has been proven in many systems, past and present. The real problem in such a system is to maintain minimum weight, volume, cost, tolerable signal losses, and high reliability.

Although a repeatered system could be developed for astronaut communications on the lunar surface, it is felt that considerable development would be involved. Thus, the author has considered only non-repeatered wire-links.

II. WIRE-LINK CONCEPT

Figure 1 illustrates the concept considered in this memorandum. As shown, the astronaut proceeds along his course and the wire is payed out behind him. When presented with such a technique, most people think that the wire would catch on

*The very small, light weight, long length hard-wire system considered does not lend itself to television transmission.

sharp edges of rocks, etc., and break. This is not true, since the wire is not dragged. The force required to pull the wire out of its dispenser, with the proper design incorporated, can be made very small. It is felt that this force amounts to a few ounces in the Astronaut Wire-Link (AWL). Thus, with only a slight amount of tension, the wire unwinds from a coiled state to a payed out state. Obviously, after a few thousand feet, the wire weight itself would be sufficient to pull additional wire out of the dispenser as it is required. Any reader who has used a spinning reel while fishing has some feel of the tension requirements. Note, however, in the AWL system it is the reel that is moving away from the unwound wire (or fishing line) not visa versa.

III. LENGTH OF WIRE-LINK AND SIGNAL FREQUENCY

As mentioned in Section I, only non-repeatered systems are considered. Consequently, the maximum distance to be traveled by the astronaut becomes very important when one strives to obtain tolerable signal losses. From Reference 1, the maximum distance is estimated to be 12 kilometers. The estimation is based on a walking speed of 4 kilometers per hour for three hours at a work load of 1600 BTU per hour. The author chooses to use 40,000 feet (slightly greater than 12 kilometers) as the maximum distance.

From Reference 2, the highest subcarrier frequency (center frequency) is shown to be 10.5 KHz. For convenience of plotting data on semi log paper, the author selected 10 KHz as an upper frequency limit.

IV. TYPE TRANSMISSION LINE

The coaxial line or the two-wire line could be used. In the selection of two-wire line, one must be careful to select a line which has a circular (or near circular) cross section as shown on Figure 2A to insure reliable wire payout. A cross section as illustrated in Figure 2B will prove very unreliable in most all cases.

The absence of moisture and the dielectric nature of the lunar surface allows one to be very conservative on insulation thickness in the selection of a transmission line. Minimum insulation thickness leads to minimum weight and volume, provided, of course, signal losses can be held to a tolerable level. Enamel insulated wire, where a dipping operation is involved rather than an extrusion operation, offers minimum insulation thickness. For example, heavy Formvar[3] only adds 6×10^{-4} inches to the radius of a number 34 AWG wire.

Truly, a coaxial cable made* with such an insulation on the inner conductor would have extremely high losses over a 40,000 ft. distance, at 10 KHz, since the capacitance per unit length would be very high. Likewise, a two conductor type transmission line with a wire spacing equal to twice this insulation thickness would have extremely high losses. This neglects the fact that a secondary insulation, thus increased weight and volume, would be required to maintain circular cross section. However, if the two-conductor wire were used with center-to-center spacings of several inches the capacitance could be reduced considerably even with the wire buried completely in the surface of the moon.**

To maintain the above mentioned wire separations and to provide reliable payout (circular cross section), the author selects the wire payout system illustrated on Figure 3. Obviously, the need for a secondary insulation has been removed. It is true that we now have two dispensers unwinding instead of one and theoretically have increased the probability of wire entanglement or breakage (breaking strength reduced), but it is felt that this system offers the minimum weight, volume, and signal losses and that the reliability can still be made very high.

Although not investigated, it is felt that noise pick-up on this configuration as compared to the coaxial cable (or two conductors spaced very close together) should not be a problem. Induced noise should be canceled to a large extent by equal and opposite current flows. Experimentation seems in order in this area.

V. BASIC DISPENSER CONFIGURATIONS

The wire-link must be wound in some sort of package (normally called a dispenser) for the astronaut to carry. Figure 4 illustrates the two dispenser configurations normally used in wire guidance systems - "Inside" payout and "Outside" payout.

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*It would be very difficult to make such a small coaxial cable in such a long length.

**Based on the worse case estimates of Lunar Conductivity and dielectric constant.[4]

The inside-payout technique (Figure 4A) requires the use of a cohesive* glue-like material to hold wire turns in place. This glue-like material is placed on the wire as it is being wound, forming something like a honeycomb. During wire payout, the wire is stripped out of this honeycomb, the glue crumbling into small particles which fall out of the dispenser. Thus, in the inside-payout scheme, the wire is essentially potted into a single unit (which can stand rather high shock and vibration levels). Of course, a lunar thermal vacuum profile must be considered in arriving at such a glue. That is, tension loads as a function of temperature and outgasing.

Outside-payout (Figure 4B) does not normally require the use of glue. However, the reliability of wire-payout can sometimes be improved by placing a small amount of glue on wire turns as the coil is being wound, particularly if the wire selected is too springy.

The outside-payout scheme, with the rather small annealed copper wire discussed in Section VII, will probably be sufficient for the AWL. If glue is found to be necessary, then the inside-payout scheme should be considered seriously.

Figure 4C shows a "reel" type storage of wire. The payout of wire stored in this manner allows the wire to lie flat on the surface. Although wire back-twisting schemes can be used on both inside and outside dispensers to reduce the amount of helix in payed out wire, it never lies as flat as it does when payed out from a reel type dispenser. However, for a given wire breaking strength, the reel type dispenser is range limited (particularly when jerky type movements are involved). That is, the entire mass of wire must be set in motion before it can be payed out. The tension loads of the inside and outside-payout dispensers are essentially independent of the total length of wire. Tension does increase somewhat as a function of dispenser diameter with the inside diameter fixed. For inside-payout, an increase in dispenser length is favored over an increase in diameter for a given total wire length, thus leading to an L/D greater than one. For outside-payout, an increased outside diameter along with an increased inside diameter is favored and the L/D is usually less than one. A reduction in tension loads can be accomplished through tapers of the wire layers and dispenser at the expense of packing density. In general, lower tension loads allow for higher wire conductivity, thus less signal losses, for a given wire volume and weight.

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*Cohesive rather than adhesive, since it is purposely designed not to adhere to the wire.

VI. COIL INDUCTANCE

With just a few thousand feet of wire wound into a coil, inductance values are in the order of henries thus the signal losses are very high. Reverse winding techniques can be used to reduce the inductance, but usually reduce the reliability of wire payout. Of course, when the coil is wound with two conductors spaced very close together, the inductance falls to a very low level but as previously mentioned the capacitive loading becomes very high. Even a coaxial line exhibits inductance values which vary during wire payout (at low audio frequencies).

For the AWL, it is felt that two dispensers should be used (as mentioned previously) and that the wire insulation should be removed periodically in winding the coil. These bared spots could then be arranged in the dispenser so that they make electrical contact as shown on Figure 5A. Solenoids of wire are shorted out as shown schematically in Figure 5B.* The bared spots could be arranged in each coil so that when both wires are payed out they are spaced far apart as shown in Figure 5C. Actually, the bared spots could be made so small that the physical diameter of the wire could not fit into the insulation crevice (Figure 5D), thus removing the necessity of spacing them as in Figure 5C. There are many other schemes, but the author feels the bared insulation technique can be expected to be quite simple and reliable.

The signal losses will essentially be zero at zero wire payout and increase as the astronaut proceeds along his course. The maximum inductance (Figure 5B) in the circuit at any one time would then be L_i. Of course, the length and diameter of the coil package selected for AWL will dictate the maximum inductance L_i and also determine amount of helix in payed out wire. The total area of bared wire must be limited since the conductivity of the lunar surface will increase the signal losses.

VII. POSSIBLE AWL CONFIGURATION

After performing several calculations and considering various trade-offs, the author arrived at the AWL described in this section and Section VIII.

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*Transients will result when these shorts are removed, but should be tolerable.

A. Wire Cross Section - The wire cross section is shown in Figure 6. It is made up of a standard #34 AWG annealed copper wire with "PYRE-M.L." wire enamel as an insulation.(5) PYRE-M.L., manufactured by DuPont, has been used commercially for about six years and it is understood to be a NASA approved insulation. It is capable of withstanding continuous temperature of 220°C. Its zero strength temperature is 150°C above the melting point of aluminum. For low temperatures, Reference 5 indicates PYRE-M.L. insulated magnet wire to withstand forward and reverse mandrel bends (1/8 inch radius) at -269°C (4° Kelvin). The tests were performed on a 25 mil diameter wire which is considerably larger than the #34 AWG discussed in this memorandum.

In the calculations of signal losses, a dissipation factor of 0.2% and a dielectric constant of 3.3 were assumed. Although these parameters vary as a function of allowed curing time (during the wire insulation process), they are felt to be easily obtained.

B. Wire Breaking Strength - In Section II, it was pointed out that tension loads should only be a few ounces since the wire is never dragged across the surface, but falls out of the dispenser as needed. The breaking strength of the above mentioned #34 AWG wire is close to 1.2 pounds, which should be more than adequate.

C. AWL Wire Spacing - The dispensers are assumed to be mounted on the astronaut's back-pack as shown on Figure 7. If wire payout tubes are used, the spacing can be adjusted over a rather wide range. For example, if the dispensers were placed one foot apart, the payout tubes could be curved outward an additional foot on either side giving a total separation of three feet. Since the capacitance and inductance (payed out wire) vary as the log of the separation, the signal losses are rather insensitive to these wire spacing changes. (See Appendix A.) This is an advantage when it is realized that wire separation will vary (they may even cross each other) as the astronaut proceeds along a curved path. Spacing variations will also be a function of wire payout tube's proximity to the surface, terrain roughness, and the amount of helix in the wire as it is payed out. In the computations of electrical characteristics, spacings of 6, 12, 24, and 36 inches are considered. Thus, data exists for just about any conceivable mounting position on the astronaut's back-pack.

D. Volume and Weight - The final selection of payout scheme, ease of mounting on the astronaut's back-pack, etc., will, of course, determine the volume required for the AWL. A rough estimate of volume can be obtained by assuming a precision wind and a simple cynlindrical shape as shown on Figure 8. Notice the cylinder shown on Figure 8 is actual size. The volume allowed for wire storage is 27 cubic inches, of which 21.2 cubic inches represents actual wire volume, thus providing a packing factor of 0.785. When glue is applied, packing factors usually run between 0.65 and 0.70.*

Neglecting the weight of end-plates, covers, payout tubes, mounting brackets, etc., the total weight of two dispensers each containing 40,000 ft. of wire is estimated to be 10.1 pounds. This estimate is based upon 0.12 lbs. per thousand feet for #34 copper wire and an additional 5% for insulation.**

VIII. CALCULATIONS OF ELECTRICAL CHARACTERISTICS

The AWL electrical characteristics were calculated for various wire spacings and signal frequencies. In all cases, the AWL is assumed terminated in its characteristic impedance. Measurements of conductivity and dielectric constant on Apollo 11 lunar surface samples may indicate that these calculations should be updated. The equations used to calculate fundamental parameters such as inductance, conductance, resisitance, and capacitance are included in Appendix A.

A. Assumed Parameters - In the calculations of electrical characteristics, the following parameters are assumed:

1) Maximum Lunar Relative Dielectric Constant[4] = 2.0

2) Maximum Lunar Conductivity[4] = 10^{-3} mho/meter

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*If the wire-turns are not wound parallel to each other (basket weave for example), packing factors can drop below these figures.

**Heavy Formvar adds about 5% to the weight of a #34 AWG copper wire. PYRE-M.L. weight was not available.

3) Upper signal frequency[2] $\simeq$ 10 KHz

4) Maximum wire length[1] $\simeq$ 40,000 ft.

5) Insulation Dissipation Factor[5] = 0.2 percent

6) Amount of helix in payed out wire negligible (Section VI)

7) Inductance effect of coiled wire negligible (Section VI)

8) Total Insulation Removal 0.125 inches/1000 ft.

B. Attenuation - Equation 1 was used to calculate the attenuation[6,7] (α) of the AWL.

$$\alpha(\text{dB}) = 8.686\left[\frac{\left[\left(R^2+\omega^2L^2\right)\left(G^2+\omega^2C^2\right)\right]^{1/2}+\left(RG-\omega^2LC\right)}{2}\right]^{1/2} \qquad (1)$$

Figure 9 shows the losses as a function of frequency and wire separations for the worse case lunar surface conditions. In Figure 10, the dielectric constant is assumed to be 1.1. The actual dielectric constant should fall between 2.0 and 1.1, since the wire will not be completely embedded in the lunar surface. In addition, the conductivity should be considerably less since the conductivity of a vacuum is involved when the wire lies above the lunar surface. The lower limit on attenuation is, of course, zero. That is, when the astronaut is still at the Lunar Module (see Section VI). Figures 9 and 10 bound the losses of wire which has been completely payed out. That is, from the standpoint of maximum and minimum dielectric constant.

With a wire separation equal to 12 inches, Figure 9 shows that an overall loss of slightly over 74 dB can be expected for worse case lunar conditions and a frequency of 10 KHz. It is felt that amplifiers could easily be designed to meet the dynamic range as well as the absolute signal levels involved in the AWL.

C. Characteristic Impedance - Figures 11 and 12 show how the characteristic impedance varies as a function of frequency, wire separation, and dielectric constant. The magnitude of Equation 2 was used in arriving at Figures 11 and 12.

$$Zo = \left(\frac{R+jWL}{G+jWC} \right)^{1/2} \quad (2)$$

D. Phase Shift (β) - Phase shifting of the signal is illustrated on Figures 13 and 14 and was calculated from Equation 3.

$$\beta\,(\text{radians}) = \left[\frac{\left[\left(R^2+\omega^2 L^2 \right) \left(G^2+\omega^2 C^2 \right) \right]^{1/2} - \left(RG-\omega^2 LC \right)}{2} \right]^{1/2} \quad (3)$$

IX. ADDITIONAL COMMENTS

A. Signal Losses - Attenuation can be reduced, thus range or signal frequency increased, by periodic inductive loading of the AWL. Of course, a high permeable tape could be wrapped around the wire to provide distributed loading, but this would probably involve considerable development and probably would increase AWL weight significantly. Reference 8 shows 0.1 henries being packaged in 0.007 cubic inches and weighing only 0.75 grams. The diameters of these inductors (0.157") are many times too large for reliable wire payout. Repackaging, however, may allow for diameters approaching the AWL wire diameter since overall inductor length is not a limiting factor in the AWL. If strain reliefs are necessary for inductor installation, rocket wire[9] (tensile strengths close to 600,000 psi) can be used.

Further reduction in signal losses may be accomplished by sending biomedical data at frequencies below 300 Hz, which is the lower cut off of voice frequencies. Thus, the AWL would only be required to operate at a frequency of 3 KHz, instead of 10 KHz. Figures 9 and 10 illustrate the benefits to be gained in this area.

B. A Measure of Distance Traveled* - Since the AWL discussed in Sections VI through VIII allows for solenoids

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*Note: As the astronaut travels further and becomes more tired, the weight of the AWL becomes less.

of wire being shorted out, a simple DC resistance monitor could be used to indicate the distance traveled by the astronaut. This information could then be telemetered to Earth over the S-Band communication link. Reflective coatings, placed periodically on the wire and photo cell devices mounted in the wire payout tube, could also be used for monitoring the amount of wire payout, thus distance traveled by the astronaut. Roughness of terrain and the amount of wire helix will influence the accuracy of such measurements, but simulations on Earth should provide correction factors.

C. Wire Breakage and Reliability - As mentioned previously, it is felt that a breaking strength of about one pound is sufficient during wire payout. However, if the astronaut were to turn completely around and catch his feet in the wire, it will break easily. The wire has very little chance of damaging his suit with such a low breaking strength, but his circular movements would need to be restricted to prevent loss of communications.

Since one astronaut can act as a relay for the other (VHF-LINK), the relay-astronaut could carry the AWL (restricting his circular movements) while the other performs tasks which require retracing of his steps.

A splicing tool could also be carried by the astronaut possibly mounted on the rod which he uses to retrieve lunar samples. Although his foot prints* should indicate the vicinity of AWL, lighting may prevent him from seeing the wire and thus, being able to make a splice.

Enamel insulated wire being very inexpensive (about $1.00 for 2000 feet of #34 AWG) allows for many AWL's to be wound and payed out here on Earth to obtain reliability numbers and to demonstrate capabilities. This is in contrast to existing r-f communication equipment where expense does not allow for manufacture in large numbers.

X. CONCLUSIONS

During lunar exploration, the transmission of the astronaut's voice and biomedical data over a very small, light

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*Note: It would be very difficult to crush this wire by stepping on it.

weight wire appears feasible. In order to provide similar signal losses for television frequencies over such a wire length, size and weight would, of course, be increased considerably.

The astronaut's circular movements would be restricted somewhat since he must be careful not to get his feet entangled in the wire and cause breakage.

The AWL described in this memorandum should be inexpensive and is essentially an off-the-shelf item.

The electrical characteristics should allow for high signal-to-noise ratios. The immunity of the AWL to induced noise, however, should be investigated.

Continuous communications will be provided for the astronaut for any elevation on the lunar surface.

William J. Benden

2034-WJB-drc W. J. Benden

Attachment
Figures 1 thru 14
Appendix A

REFERENCES

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5. DuPont Bulletin #19, Pyre-M.L. Wire Enamel, August, 1967.

6. Breazeale, W. M. and Quarles, L. R., Lines Networks and Filters, International Textbook Company, January, 1951.

7. Ramo, S., VanDuzer, T., and Whinnery, J. R., Fields and Waves in Communication Electronics, John Wiley and Sons, Inc., 1965.

8. Ibid, Electronic Engineers Master, p. 741.

9. National-Standard Company Technical Bulletin, High-Tensile Wire, December, 1960.

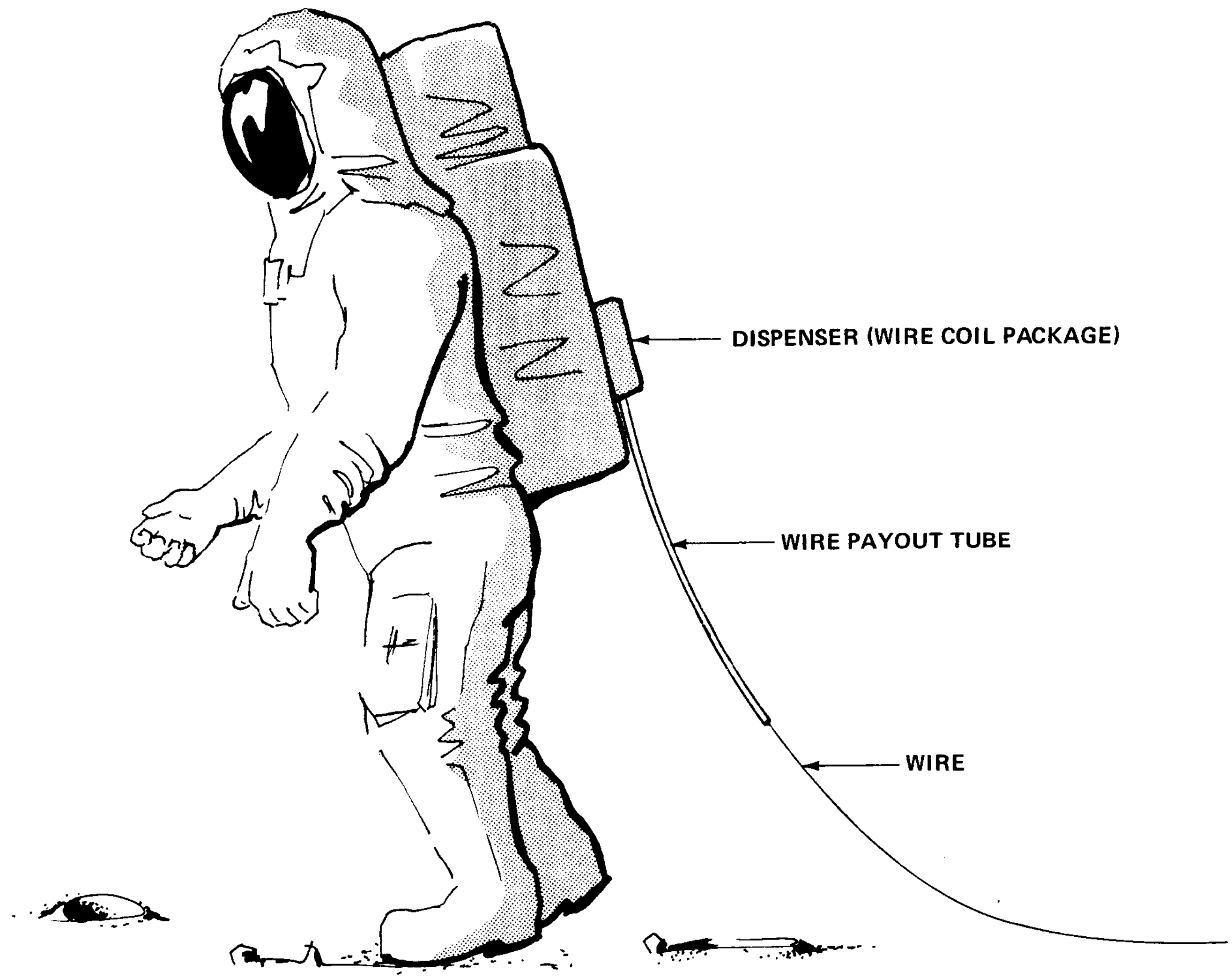


FIGURE 1 - ASTRONAUT WIRE LINK CONCEPT

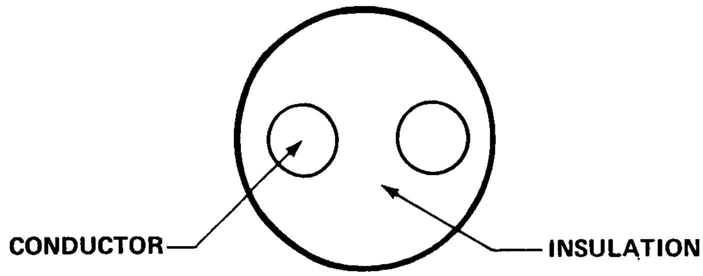


FIGURE 2A- TWO WIRE CIRCULAR CROSS SECTION FOR RELIABLE PAYOUT

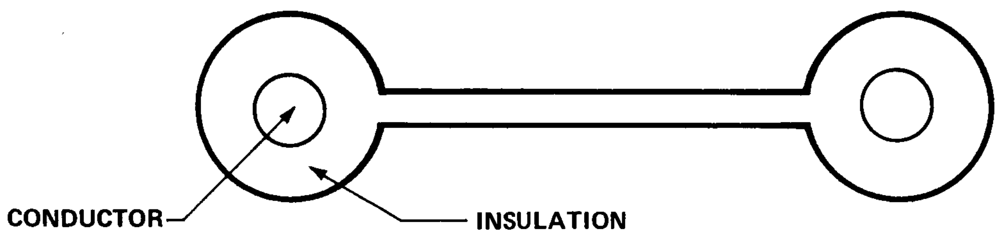


FIGURE 2A- TWO WIRE CIRCULAR CROSS SECTION FOR RELIABLE PAYOUT

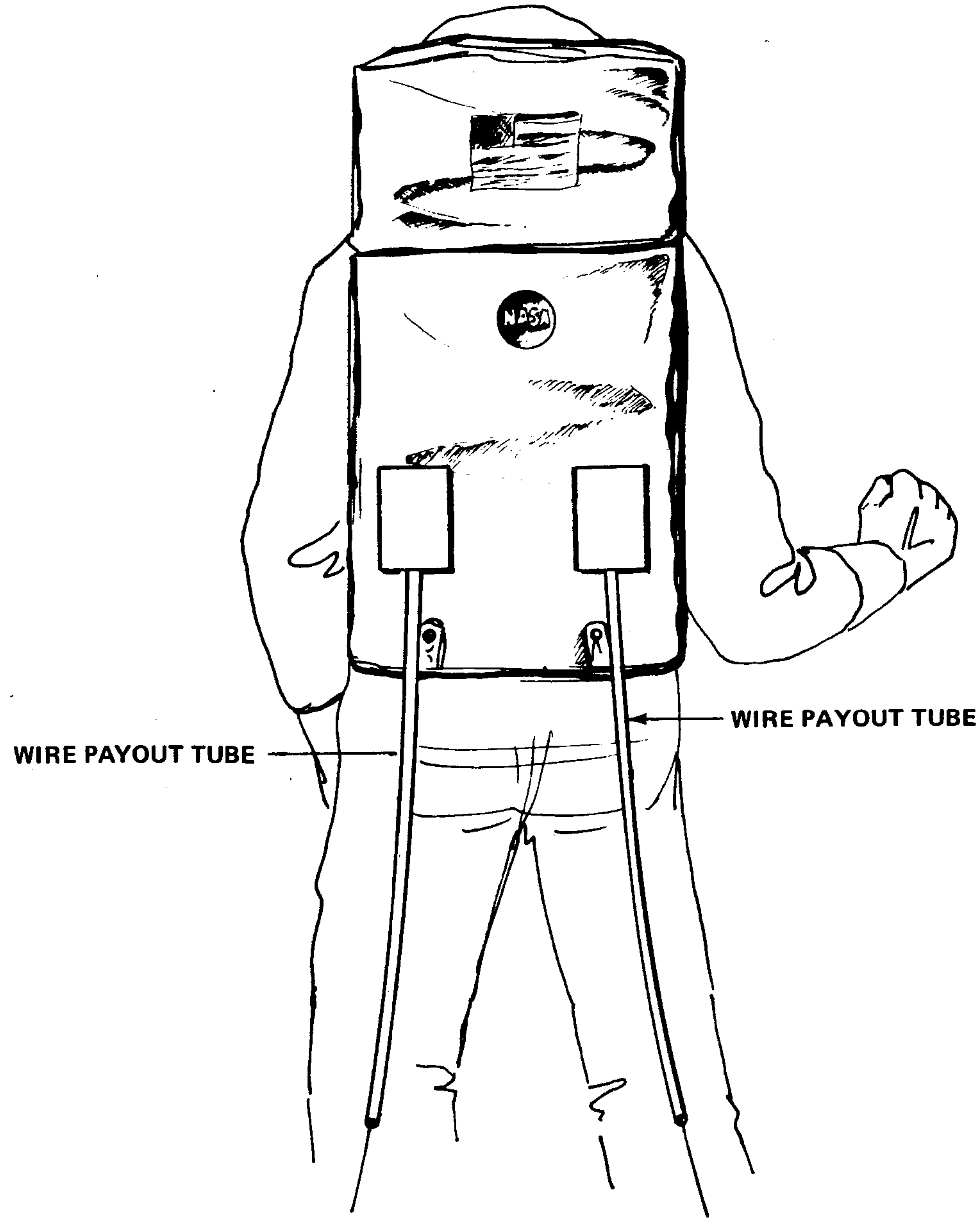
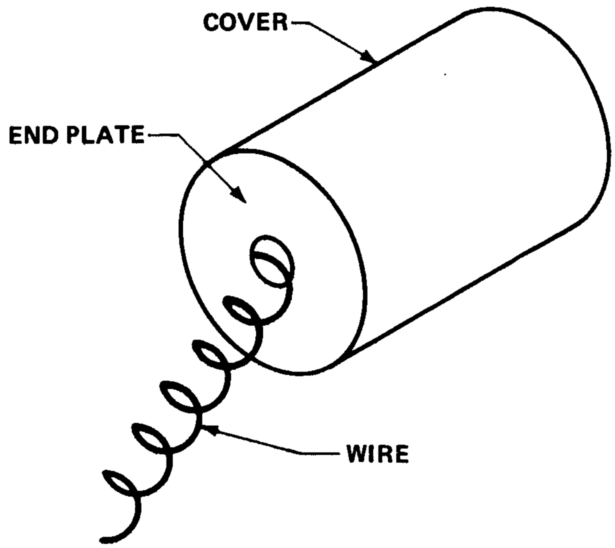


FIGURE 3 - ASTRONAUT UTILIZING TWO DISPENSERS - ONE FOR EACH CONDUCTOR



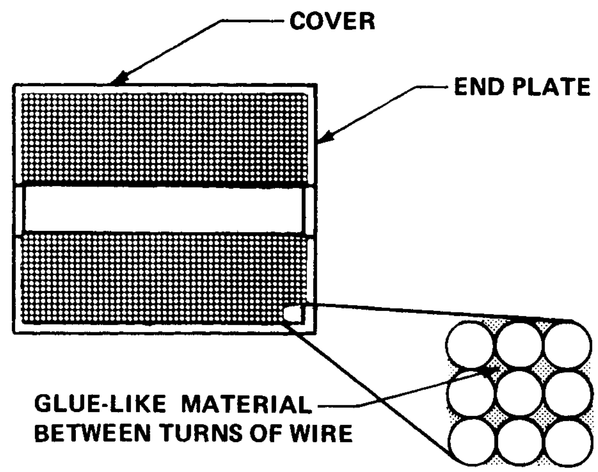
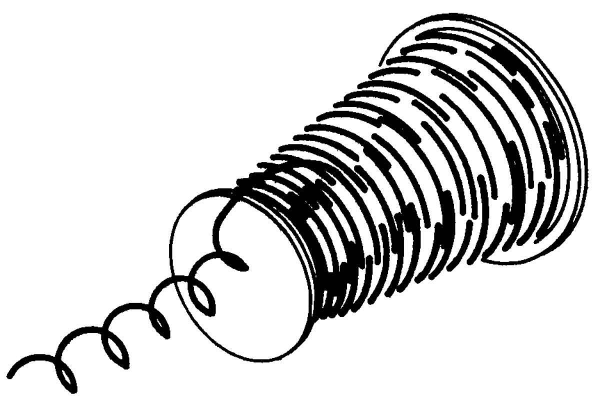


FIGURE 4A- INSIDE PAYOUT



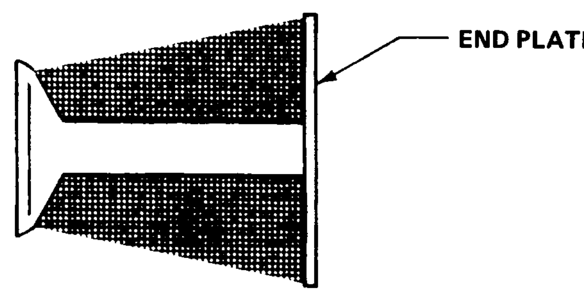


FIGURE 4B - OUTSIDE PAYOUT

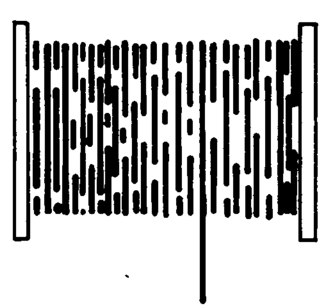


FIGURE 4C- REEL TYPE PAYOUT

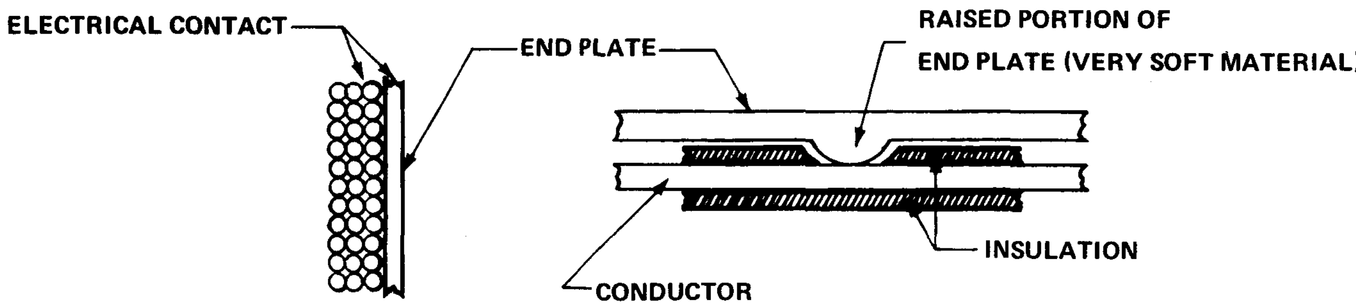


FIGURE 5A- BARED INSULATION - ELECTRICAL CONTACT WITH END PLATE

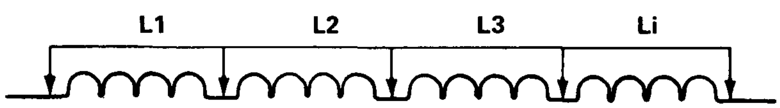


FIGURE 5B- SOLENOIDS - SHORTED OUT

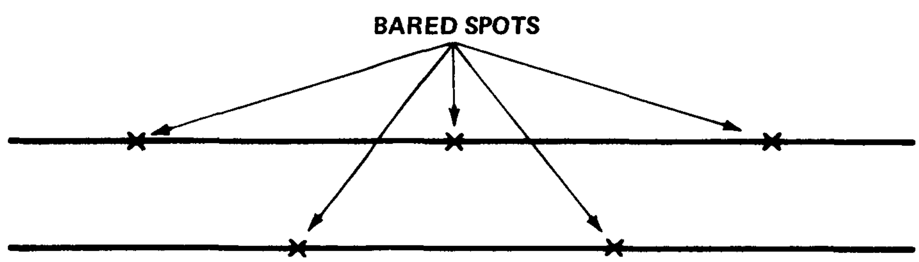


FIGURE 5C- SPACING OF BARED SPOTS AFTER WIRE PAYOUT

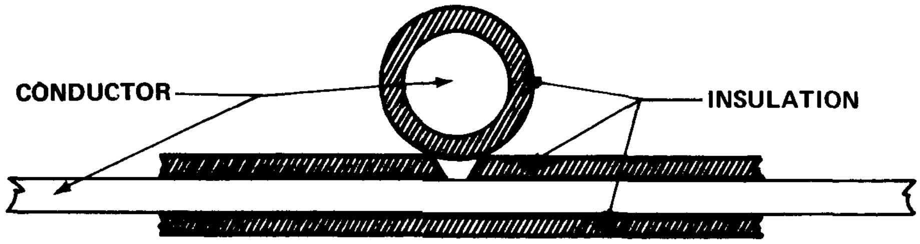


FIGURE 5D- INSULATION CREVICE TOO SMALL TO ALLOW SHORTING OF TWO WIRES TOGETHER

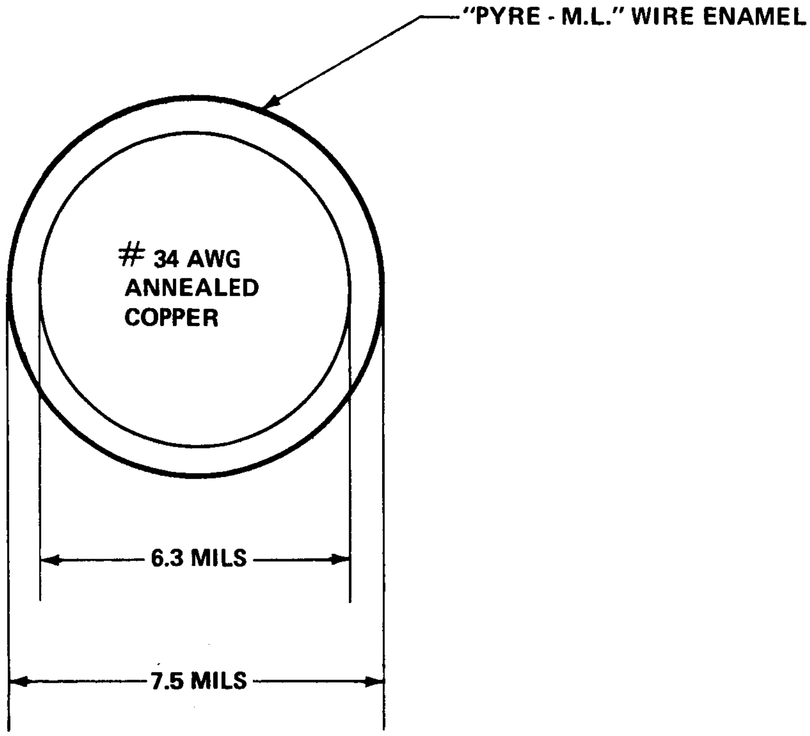


FIGURE 6 - WIRE CROSS SECTION

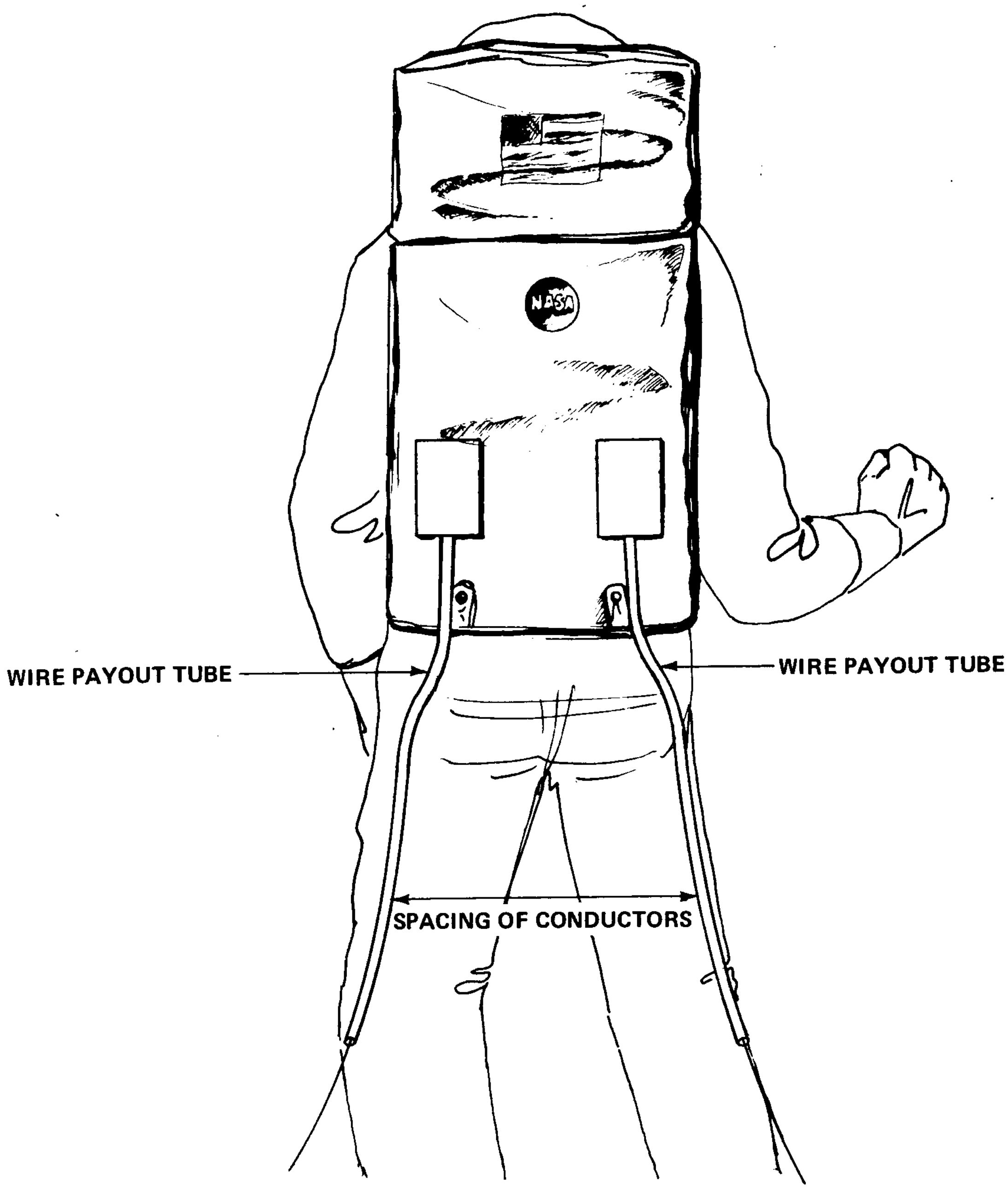
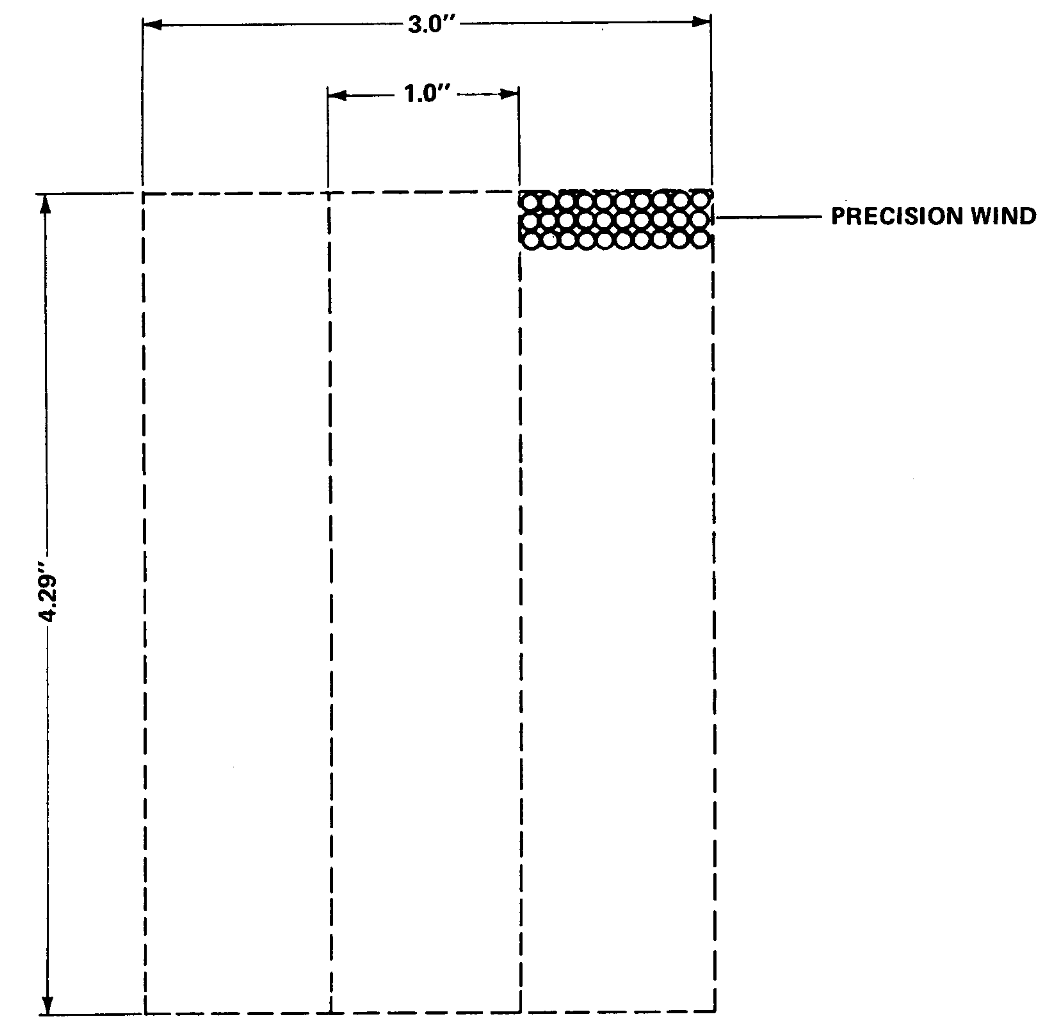


FIGURE 7 SPACING OF CONDUCTORS



ACTUAL SIZE - PRECISION WIND – 40,000 FEET
WEIGHT $\simeq$ 5 POUNDS — NOT INCLUDING DISPENSER HARDWARE

FIGURE 8 - ESTIMATE OF AWL VOLUME AND WEIGHT

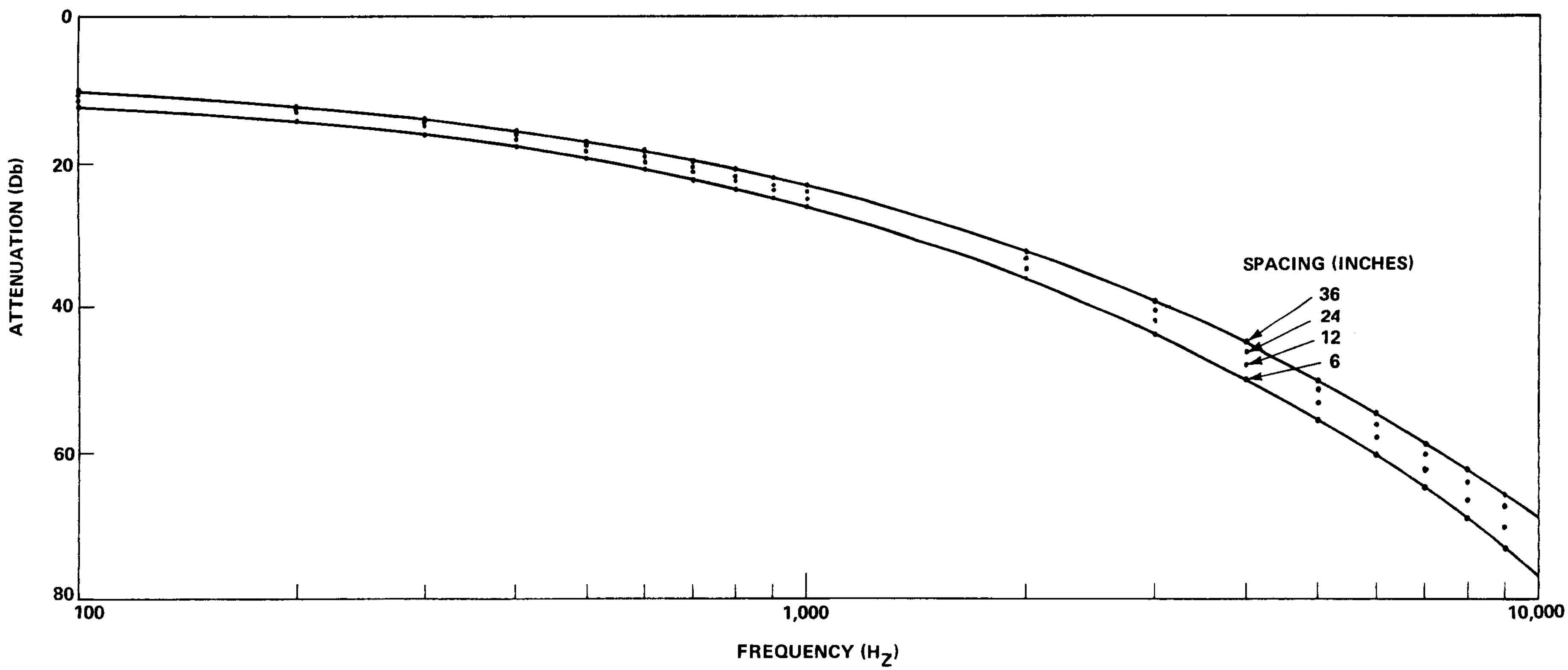


FIGURE 9- ATTENUATION VS. FREQUENCY, 40,000 FT. AWL
(LUNAR DIELECTRIC CONSTANT=2.0, TEMPERATURE=120°C)

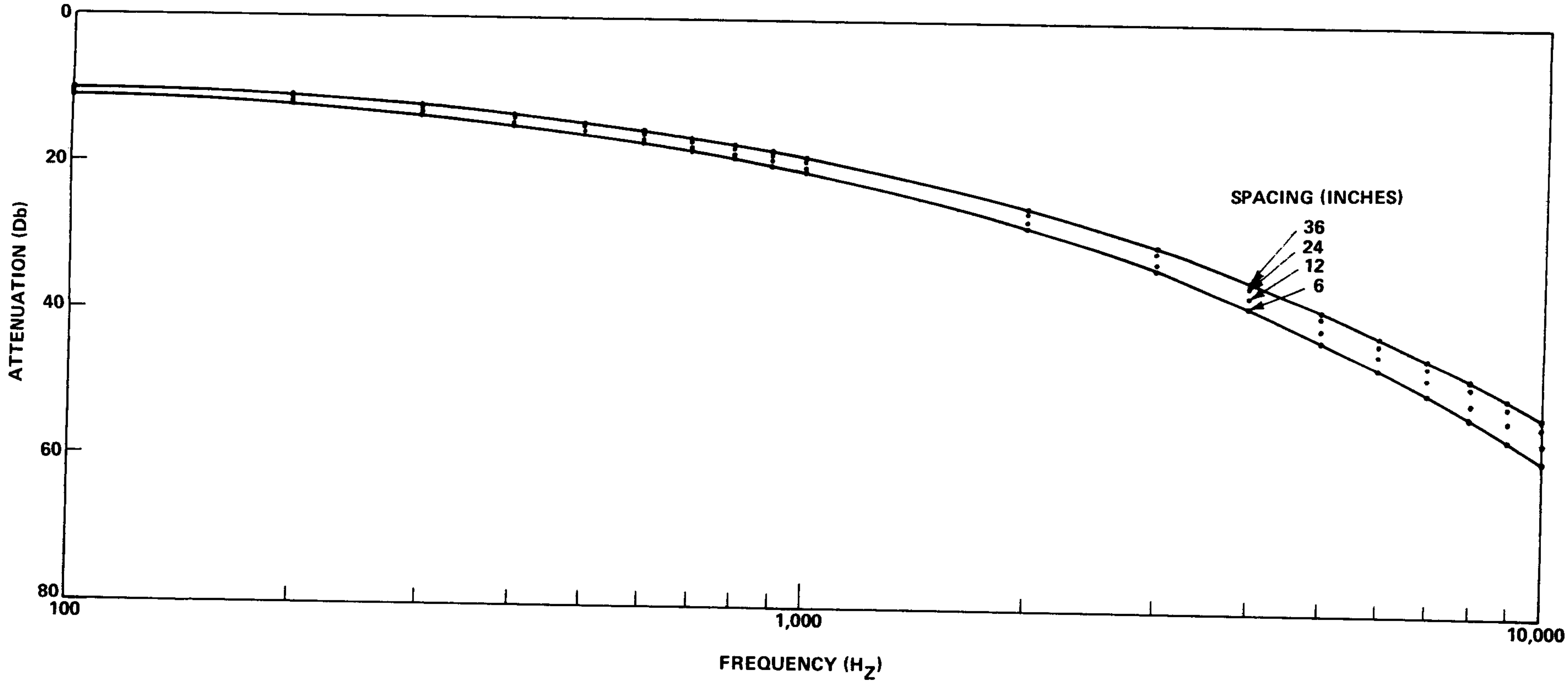


FIGURE 10- ATTENUATION VS. FREQUENCY, 40,000 FT. AWL
(LUNAR DIELECTRIC CONSTANT=1.1, TEMPERATURE=120°C)

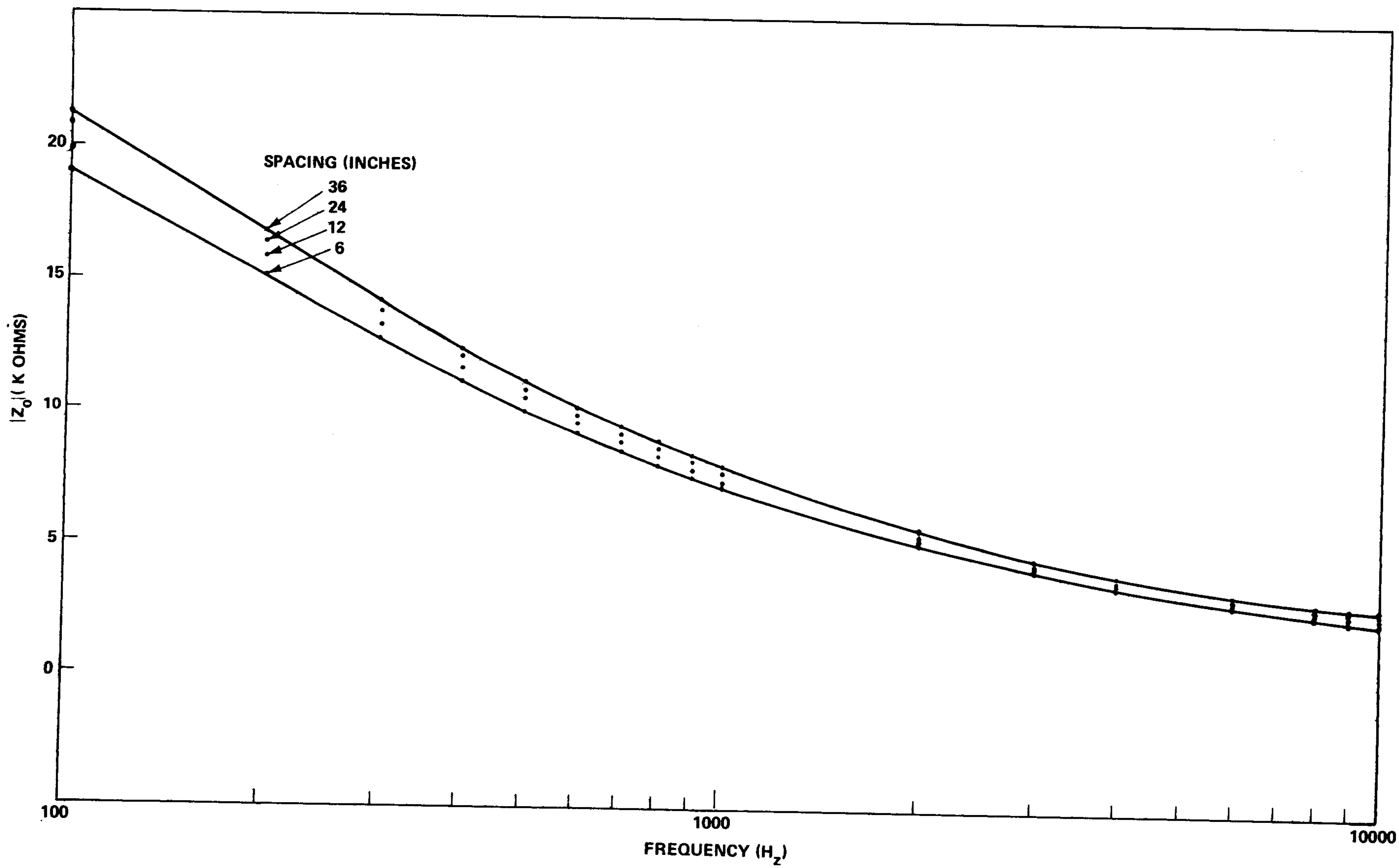


FIGURE 11- CHARACTERISTIC IMPEDANCE VS. FREQUENCY
(LUNAR DIELECTRIC CONSTANT=2.0,TEMPERATURE=120°C)

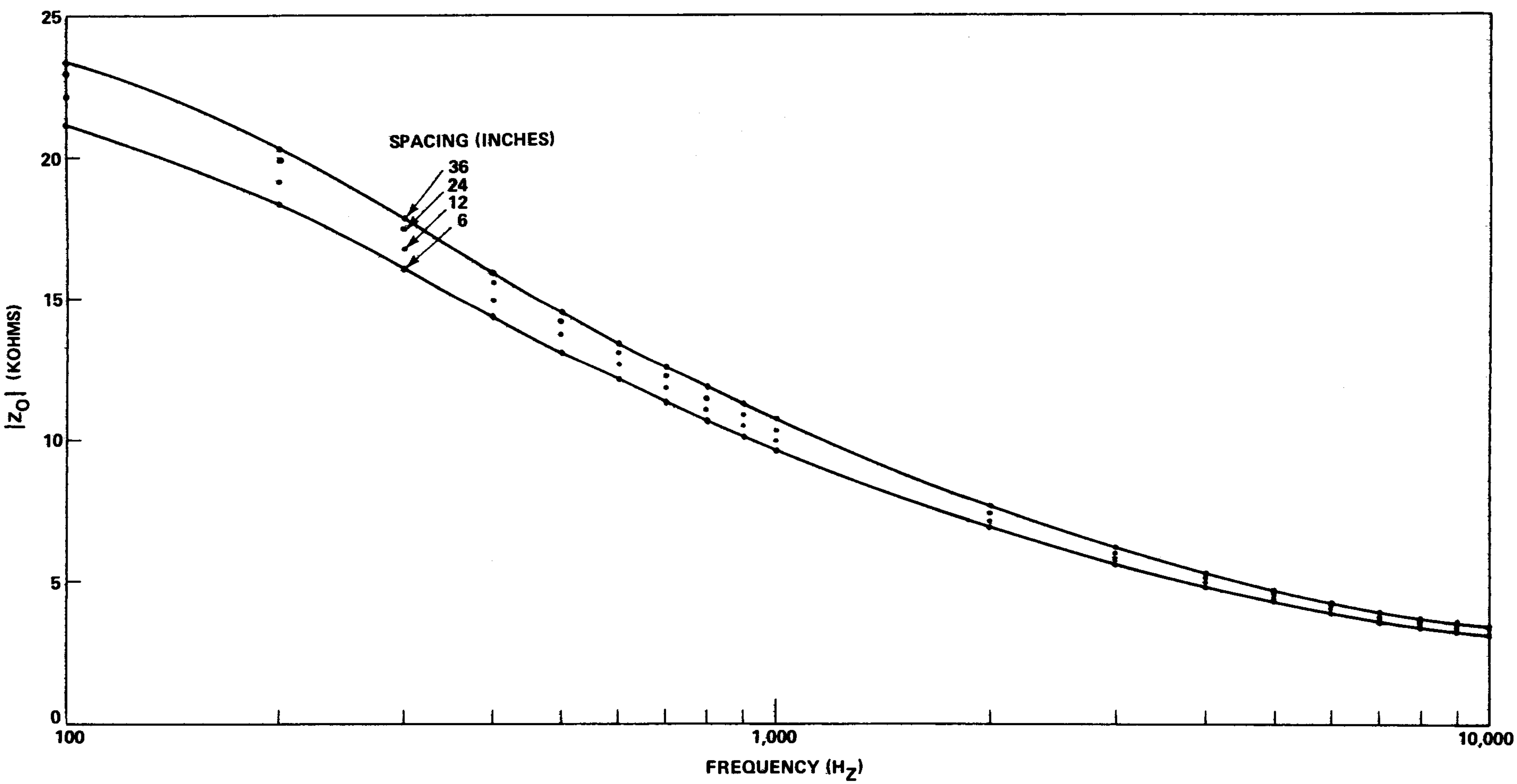


FIGURE 12- CHARACTERISTIC IMPEDANCE VS. FREQUENCY
(LUNAR DIELECTRIC CONSTANT=1.1, TEMPERATURE=120°)

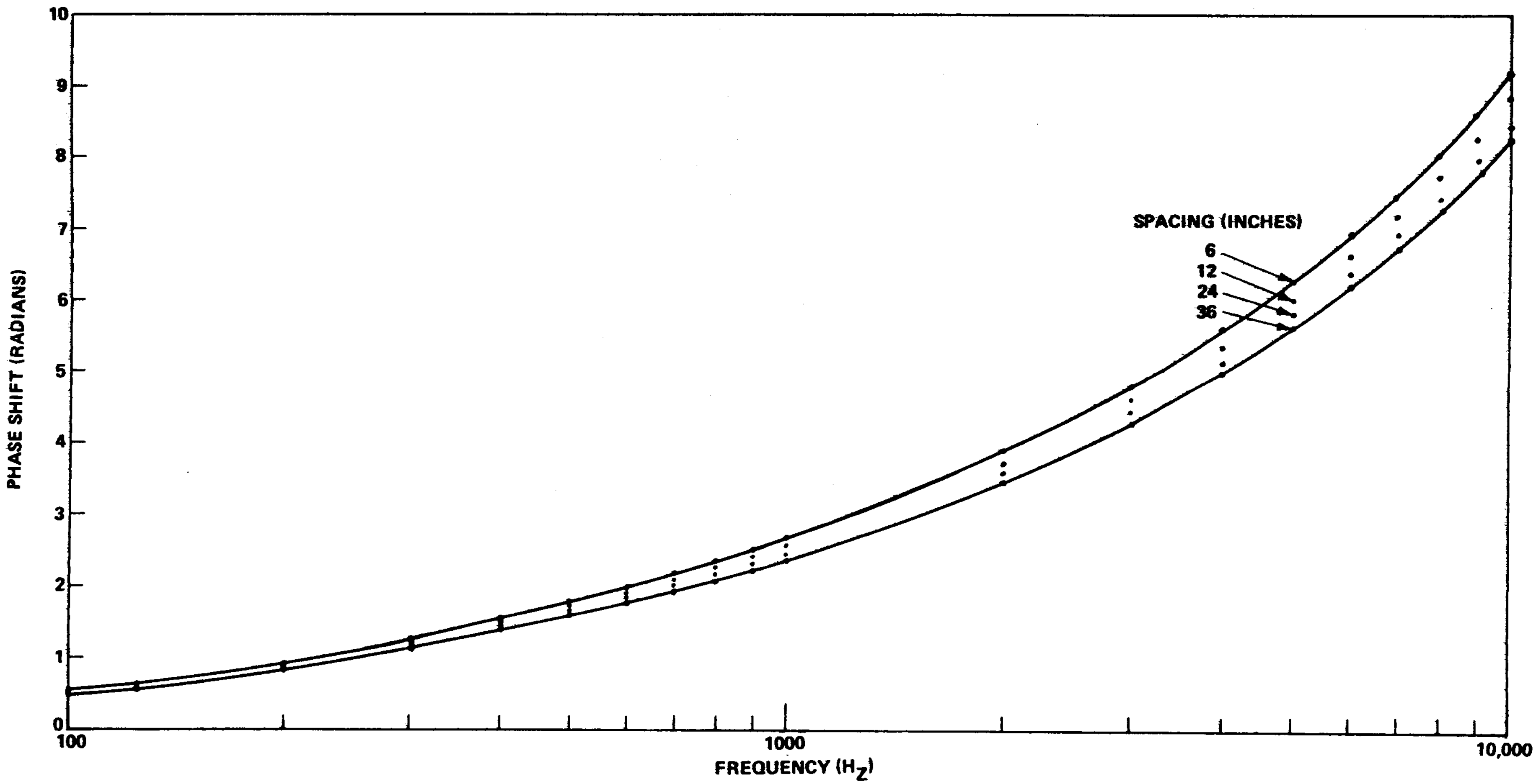


FIGURE 13- PHASE SHIFT VS. FREQUENCY, 40,000 FT. AWL
(LUNAR DIELECTRIC CONSTANT =2.0,TEMPERATURE =120^{o}C)

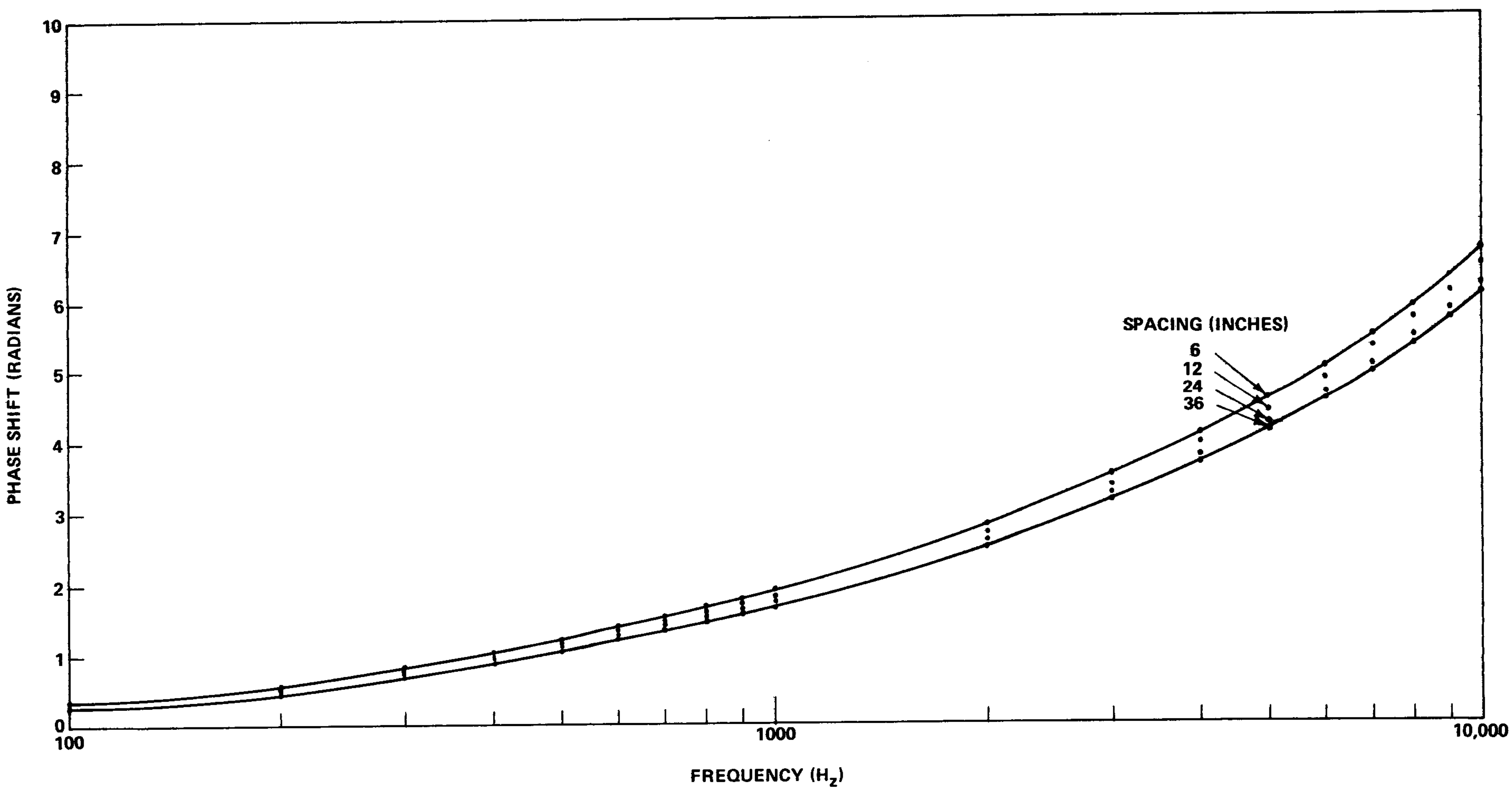


FIGURE 14- PHASE SHIFT VS. FREQUENCY, 40,000 FT. AWL
(LUNAR DIELECTRIC CONSTANT =1.1, TEMPERATURE=120°C)

APPENDIX A

Fundamental parameters of inductance, conductance, capacitance and resistance were calculated for the frequencies of interest. These parameters were then used to calculate attenuation, characteristic impedance, and phase shift.

A. Inductance and Capacitance - The inductance was calculated from Equation A-1 and capacitance from Equation A-2.

$$L = \left(3.04 \times 10^{-2} + 1.215 \times 10^{-1} \ln d/a\right) \text{ milihenry/1000 ft.} \quad \text{(A-1)}$$

$$C = \frac{\Pi \varepsilon}{\cosh^{-1} \frac{d}{2a}} \quad \text{(A-2)}$$

where

d = wire center to center spacing

a = wire radius

$\varepsilon = \varepsilon_r \cdot \varepsilon_o$, ε_r = lunar* relative dielectric constant

ε_o = permitivity of free space

Notice that the first term in Equation A-1 accounts for the internal or low frequency inductance. Skin effect is negligible in this small diameter wire with the upper most frequency being $\cong$ 10 KHz. Although Equation A-2 includes proximity effects, Equations A-1 and A-3 do not. The spacings utilized in the calculations are sufficient to make proximity effects negligible.

B. Resistance and Conductance - Equations A-3 and A-4 were used for calculating resistance and conductance.

$$R_{DC} = R_{20}\left[1 + \rho_{20}\left(T-20\right)\right] \quad \text{(A-3)}$$

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*Insulation dielectric constant has essentially no effect at the various wire spacings assumed.

APPENDIX A

where

R_{20} = DC resistance at 20° centigrade

ρ_{20} = constant for copper = 3.93×10^{-3}

T = temperature of wire in °C

$$G = \frac{G_1 G_2}{G_1 + G_2} + G_3 \qquad \text{(A-4)}$$

where

$G_1 = \dfrac{\Pi\omega\varepsilon''}{\cosh^{-1}\left(d'/2a\right)}$, ε'' = loss factor of insulation

$G_2 = \dfrac{\Pi\sigma}{\cosh^{-1}\left(d/d'\right)}$, σ = lunar conductivity

$G_3 = \dfrac{\Pi\sigma}{\cosh^{-1}\dfrac{d}{2a}}$, σ = lunar conductivity

Spacings d' and d need some explanation. The separation d' is used for calculating G_1 so that the conductance allowed by the insulation is obtained. That is, the insulated wires are assumed to be touching and having only enamel between them. G_2 is then found by assuming the insulated wire to be a solid bare copper wire of diameter d' spaced at a distance equal to d, thus obtaining the lunar* surface contribution to conductance. Finally, G_3 accounts for the conductance caused by the bared portion of wire (see Section VI) while spaced at the actual physical separation d.

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*As mentioned previously, to obtain worse case conditions it is assumed that the wire is completely embedded in the lunar surface.

BELLCOMM, INC.

Subject: Astronaut Wire Communication Link During Lunar Explorations - Case 320

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